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Sustainable energy systems in an imaginary island

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ABSTRACT

The study of sustainable energy systems is an interdisciplinary endeavour which entails the analysis of a large amount of diverse data and complex interactions that are better understood if developed from first principles. This paper reviews the approaches to this analysis and presents as a general case study, a fossil free imaginary island whose electricity, heat and mobility demand are fulfilled with sustainable and renewable energies only. The detailed hourly balance between supply and demand highlights the importance of energy storage, which is achieved by reversible hydropower and storage in electric vehicles.

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1. Introduction

The analysis of a sustainable energy system is a complex interdisciplinary exercise that involves a thorough understanding of technology, physics, electrical engineering, modelling, economics and sociology. Teaching energy systems, in particular to a heterogeneous audience, thus becomes a challenge which can be facilitated by the development of particular case studies that illustrate the most relevant issues that can emerge in this area.

Sustainable energy systems are usually approached with the support of software packages designed for that purpose [1]. However, from the educational point of view, it is more interesting to tackle the problem from scratch. The results will certainly be less realistic as assumptions will be made to make the problem more tractable in the available time frame. This methodology may also be useful at the early stages of a feasibility analysis for a particular project. It provides a comprehensive view of the problem, of its variables and constraints, which is a crucial requirement for choosing the most suitable software package for further in-depth studies. Additionally, hidden parameters and variables are exposed to those outside the renewable energy circle, such as policy makers and investors.

Our study departs from a fictional case study, which has served as the backbone of a course on sustainable energy systems for engineering students at the University of Lisbon. Its overall purpose is to design a fossil free energy system for an isolated region, an imaginary remote island whose main characteristics were arbitrarily set and are presented in Table 1. Besides this, the only data used are the solar radiation, wind speed, temperature and precipitation time series, and typical load diagrams for the corresponding climate data.

This paper presents an overview of the state of the art Sustainable Energy System (SES) methodologies for isolated systems and describes the complete analysis of the energy system of the fictional case study, including electricity supply and demand, heating and mobility, thus detailing the methodology used to build a 100% renewable energy system from scratch. This methodology requires reviewing the different renewable energy technologies, energy demand conditioning tools and energy storage alternatives, which are extensively discussed.

2. Overview of SES analysis

Sustainable energy systems with 100% renewable energy share require an understanding of the renewable energy resource characteristics and availability and how can the different available technologies be integrated and managed in order to meet the energy demand. A well cemented understanding of the problem should be built upon a gradual approach, starting from basics and preferably without the use of a dedicated computer tool for the purpose that, more often than not, acts as a black box to the user. This approximation allows gaining sensibility to the subject, which enables the proper choice of the appropriate tool for a particular application, helping in the preparation of the input data and the critical analysis of the outputs.

An approach of this type is presented by Mackay in 'Without the hot air' [2], a well-known and fruitful discussion of sustainable energy systems from first principles. Here, the potential of different renewable sources for the UK are individually analysed and are then articulated to match energy demand. The potential of energy storage is briefly reviewed, but it is only considered on an annual scale and not on a more detailed level, such as on an hourly scale. It concludes that in UK around 92% of the energy demand can be fulfilled by renewables. However, an integrated sustainable energy plan requires temporal simultaneity of energy consumption and production, an analysis not performed in 'Without the hot air'.

Jebaraj and Iniyan [3] present a broad review of energy models. They identify various emerging issues related to the energy modelling, covering models of energy planning, energy supply and demand, forecasting, renewable energy, emission reduction and optimization. Also, models based on neural network and fuzzy theory are reviewed and discussed. On the other hand, Connolly et al. [1] review computer tools for analysing the integration of renewable energy into energy systems. In order to aid the selection of a suitable energy tool for a particular application, 37 different software tools are comprehensively analysed. The paper contains individual descriptions of each of the energy tools reviewed, outlining the context of the information provided, and provides a sample of the existing studies completed by each of the energy tools in consideration. The authors conclude that there is no energy tool that addresses all issues related to integrating renewable energy.

Wide analyses of particular 100% renewable energy systems have been conducted in many studies and a review of them is presented by Lund et al. in [4]. The range of applicability goes from the town level to global scenario level, including countries of different sizes although none is focused on small isolated regions. Østergaard and Lund [5] outline the energy situation of the Danish city of Frederikshavn, including all electricity, heating and transportation demands, developing a technical scenario for the transition to an energy system based on locally available RES such as geothermal, wind off-shore, biogas and waste. Special focus is given to the impacts of geothermal energy on the energy system dynamics. Also in Denmark, Lund and Mathiesen [6] and Mathiesen et al. [7] present a methodology including hourly computer simulations and propose a series of required changes to the "business as usual" reference scenario to achieve 50% of RES in 2030 and 100% of RES in 2050. It includes a socio-economic feasibility study of the 2030 system, the marginal feasibility of each individual proposal, socio-economics costs, health costs, commercial potential and job creation, and the energy balances

Table 1
Island general assumptions.

Population	50,000
Population density	100 person/km^2
Average family size	2.5 person
Number of cars	0.5 car/person

by source, fuel consumptions and CO_2 emissions for both 2030 and 2050 scenarios. Connolly et al. [8] focuses on three different scenarios (biomass, hydrogen and renewable generated electricity based systems) and a fourth one combining all three together, to achieve a 100% RES supply system for Ireland. A similar approach is developed by Krajačić et al. [9] for Portugal. Three scenarios are tested, including one 100% RES, and the authors conclude that if all the exchanged electricity with the exterior is RES based, it will be possible to achieve a 100% RES electricity supply within a 10 years frame. A long term sustainable solution for China is analyzed by Liu et al. in [10]. The article presents the current development of RES in the country and discusses its potential. Then, it makes a comparison with Danish situation and it determines that it is suitable to adopt a similar methodology of RES implementation in China. Considering that the renewable energy resources in the country are abundant and can cover the demand, the authors conclude that proposing a 100% renewable energy system in China is not unreasonable.

At the global and regional levels, Føyn et al. [11] perform a modelling exercise aiming to test ETSAP-TIAM energy system model in order to achieve a 100% global renewable energy system. A 100% RES system is not achieved, but the model comes close to exploit several of the RES limits, which indicates that the data on renewable resources potentials must be refined. Another conclusion is that the IPCC 2C target [12] will be very expensive to reach.

In Australia, Elliston et al. [13] discuss 100% renewable energy systems to meet 2010 hourly electricity demand. It is shown that the most challenging issue is how to fulfil demand on non-windy winter evenings after periods of consecutive clouded days when concentrated solar thermal storage is at low levels. Reduction in peaking capacity through demand response strategy was assessed, concluding that a significant reduction in peaking capacity can be achieved with carefully designed demand-side policies. Another approach to simulate a 100% renewable energy sources (RES) based system at a country level (New Zealand) is presented by Mason et al. [14]. Here the authors removed the fossil fuel based production from a 3 year data set of half-hourly historic electricity production and replaced it by modelled electricity production from wind and geothermal energy sources. Peaking management was modelled using demand side response, biomass gas generation, pumped storage hydro and additional conventional hydro. Again, demand-side policies were shown to have considerable advantages over installation of new peaking plants. On another study, Ćosić et al. [15] analyses the implementation of two renewable scenarios designed for the years 2030 and 2050 in Macedonia with 50% and 100% RES shares, respectively. Special emphasis is given to the articulation between intermittent RES and storage technologies. The authors conclude that the RES 50% scenario could be easily achieved with new energy efficiency measures leading to demand reduction.

Table 2
Summary of literature overview of energy systems with a high share of renewable energy.

	Back of envelope approach	Isolated systems[a]	Hourly or thinner analysis	Economic analysis	*Notes*
Large scale					
MacKay [2]	✓	✓		✓	Simple and meaningful approach to energy planning in the UK context. Detailed analysis of match between supply and demand is not performed
Østergaard and Lund [5]			✓		100% RES supply of the Danish city of Frederikshavn is simulated using EnergyPLAN. Special focus on the use of geothermal energy. Primary energy consumption can be reduced by 26%, mainly through changes in the production system
Lund and Mathiesen [6] and Mathiesen et al. [7]			✓	✓	100% Renewable energy system by the year 2050 is simulated for Denmark using EnergyPLAN and incorporating a socio-economic analysis
Connolly et al. [8]			✓		Four 100% renewable energy systems using EnergyPLAN were simulated for Ireland with each three focusing on a different resource and a fourth being a combination of each
Krajačić et al. [9]		✓	✓		Study is for Portugal using H_2RES software and RenewIslands methodology, being conducted an analysis as if the country was an isolated system
Liu et al. [10]				✓	RES potential and objectives for China are analysed, being compared with Danish situation. Detailed analysis is not performed
Føyn et al. [11]				✓	ETSAP-TIAM global energy system model (TIMES based partial equilibrium model) is tested towards a 100% RES global supply
Elliston et al. [13]			✓		Simulation was performed using a program written in Python programming language developed by the lead author
Mason et al. [14]		✓	✓		Simulations were performed half-hourly using Matlab.
Ćosić et al. [15]			✓	✓	Authors conclude that biomass needed for a 100% RES based system may not be available. Simulations were carried on EnergyPLAN
Islands					
Krajačić et al. [26]			✓		Application of the H_2RES model [22] to the island of Mljet. Several scenarios, with different choices of renewable technologies (PV and wind), hydrogen for transport and storage, grid connection, are presented. A 100% renewable island scenario is feasible
Kaldellis et al. [27]		✓	✓	✓	Estimation of energy (electricity and thermal), water demand and RES potential (solar, wind and biomass). HOMER simulation to ensure energy autonomy. The proposed system includes wind turbines, PV panels, batteries and a biogas electrical generator
Singal et al. [28]	✓	✓		✓	Sizing of a RES system on an annual average basis, without software optimization. It is suggested to replace the existing diesel generating plant by a biogas power plant, a biomass gasification plant, a PV system and batteries for storage
Praene et al. [29]		✓			Assessment of current energy situation and consumption of Reunion island and evaluation of renewable energy potential. Description of the PRERURE energy plan, aiming for a 100% RES supply on 2030
Bağcı [30]	✓				Study about Peng Chau Island, Hong Kong. The combination of solar, wind and wave energy are shown to be the most suitable option to achieve energy autonomy from mainland

[a] With isolated systems we mean systems with limited or absent energy trades with other regions, like most of islands.

Table 3
Overview of reviews on energy systems with a high share of renewable energy.

	Models review	Computer tools review	100% renewable systems	RES integration	Notes
Connolly et al. [1]		✓			37 tools were analysed and compared but just four have been used previously to simulate 100% renewable energy-systems
Jebaraj and Iniyan [3]	✓				It gives a brief overview of the various methods for energy modelling
Lund et al. [4]			✓	✓	Provides a review of the works presented at the 2009 SDEWES Conference [31]
Duic et al. [32]			✓	✓	RenewIslands methodology for the assessment of alternative scenarios for energy and renewable resource planning
Duic et al. [22]			✓	✓	H2RES model for optimisation of integration of hydrogen usage with intermittent RES in island energy systems

On a smaller scale, several studies about integrating RES in remote islands have also been performed. Most of the cases studies consist on hybrid renewable energy systems, where the integration of new RES is made upon existing energy supply systems, typically a diesel power plant connected to a small distribution grid. The increase of RES share can help mitigate the raising costs of fossil fuels and gain autonomy from mainland energy imports, which ultimately leads to higher levels of system reliability and supply security. An extensive review on hybrid renewable energy systems is presented by Neves et al. [16].

Evaluating the renewable potential and modelling possible scenarios for increasing RES share is the goal of several articles: Andaloro et al. [17] addresses the case of Salina Island near Sicily, Italy, with special emphasis on summer months due to the higher demand from tourism; Katsaprakakis et al. [18] proposes a 90% renewable system with PV, wind turbines, batteries and a diesel generator as a backup for Dia Island in Greece; Kaldellis et al. [19] presents an optimal wind-hydro solution for a couple of islands in the Aegean Sea near Greece, with a renewable energy sources penetration exceeding 85% of total demand; Babarit et al. [20] studies the Yeu Island in France, to be supplied by marine renewables (offshore wind and waves), balancing the size of local battery storage with grid import from mainland; Bueno et al. [21] develops a wind powered pumped hydro storage system to increase the RES share in Canary Islands, reducing fossil fuel imports; and, finally, the application to the H_2RES model for optimisation of integration of hydrogen usage with intermittent RES [22] in the case studies of the islands of Porto Santo, Portugal [23], Corvo Azores, Portugal [24] and Cape Verde [25].

More ambitious targets of 100% RES supply, are addressed by Krajačić et al. [26], which draws different scenarios for Mljet Island, Croatia, where energy autonomy could be obtained using fuel cell, electrolyser and hydrogen storage technologies; Kaldellis et al. [27] describes the HOMER software optimization of a RES system to satisfy electricity, water and thermal demands, in Agathonisi Island, Greece; Singal et al. [28] shows that it would be environmental and economically advantageous to replace the existing diesel generating plant with biomass, PV and batteries, and they can fulfil the energy demands of five isolated villages in the remote Neil Island, India; Praene et al. [29] makes an assessment of the available RES and their current contribution for the energy system and also describes the energy plan for the French Reunion Island, in which the main objectives are to diversify the energy mix and make it 100% renewable until 2030; and finally Bağcı [30] proposes a solar, wind and wave energy system to gain energy autonomy In Peng Chau Island, Hong Kong. A common denominator in all these case studies is the need for a backup system, whether it be batteries, hydrogen fuel cells or a biomass-fired steam power plant.

Table 2 presents a systematic summary of the most relevant analysis of sustainable energy systems aiming for 100% renewable energy existing in the literature. Emphasis is given to the share of renewables, if the system is isolated in the sense that it does not allows for energy trade with neighboring systems, which is the case of most isolated islands, if an hourly analysis between energy demand are supply is performed and if it includes an economic analysis. Also, Table 3 includes a summary of other existing reviews on these subjects.

3. Energy supply

In this section we analyse the energy supply potential from the local renewable resources of the imaginary island. We consider production of electricity, heat and also biofuels for transport. The resources are diverse such as biomass, solar, wind and hydro.

3.1. Island characteristics

In order to assess the potential of the different technologies, one has to survey the available energy resources. For an imaginary island one may produce synthetic data sets for a typical climate. Instead, we provide real time series for temperature, solar, wind and rain from an unspecified location. Fig. 1 shows these time series and Table 4 summarises its main features. Due to the association between the cold and rainy seasons and the mild Winter and Summer, one can easily observe that these time series are typical of a southern European temperate climate, which will of course determine the particular final solution. Nonetheless, we do not believe the generality of the approach described below is lost.

The river flow time series may be determined from the precipitation time series by defining two time constants. This first ($\tau_1 = 1$ day) is due to surface water flow and the second ($\tau_2 = 6$ months) due to ground water flow. The river flow is then determined by the fraction of surface and ground water flow (assumed to be 20% and 40% of the precipitation, respectively); these need not necessarily add up to one, as losses, such as evaporation, can also be considered. The overall magnitude of the river flow is determined by the size of the river basin (assumed to be 100 km^2). Using these assumptions, the river flow time series on the nth day is calculated using:

$$\Phi_n = \sum_{i=n-365}^{n} \left(\frac{C_1}{\tau_1} \Phi_i \, e^{-(T(i,n)/\tau_1)} + \frac{C_2}{\tau_2} \Phi_i \, e^{-(T(i,n)/\tau_2)} \right) \quad (1)$$

where $T(i,n)$ is the time difference (in days) between day i and day n.

3.2. Electricity supply

The renewable electricity supply is determined using the solar radiation, wind and rain time series. We focus only on mature

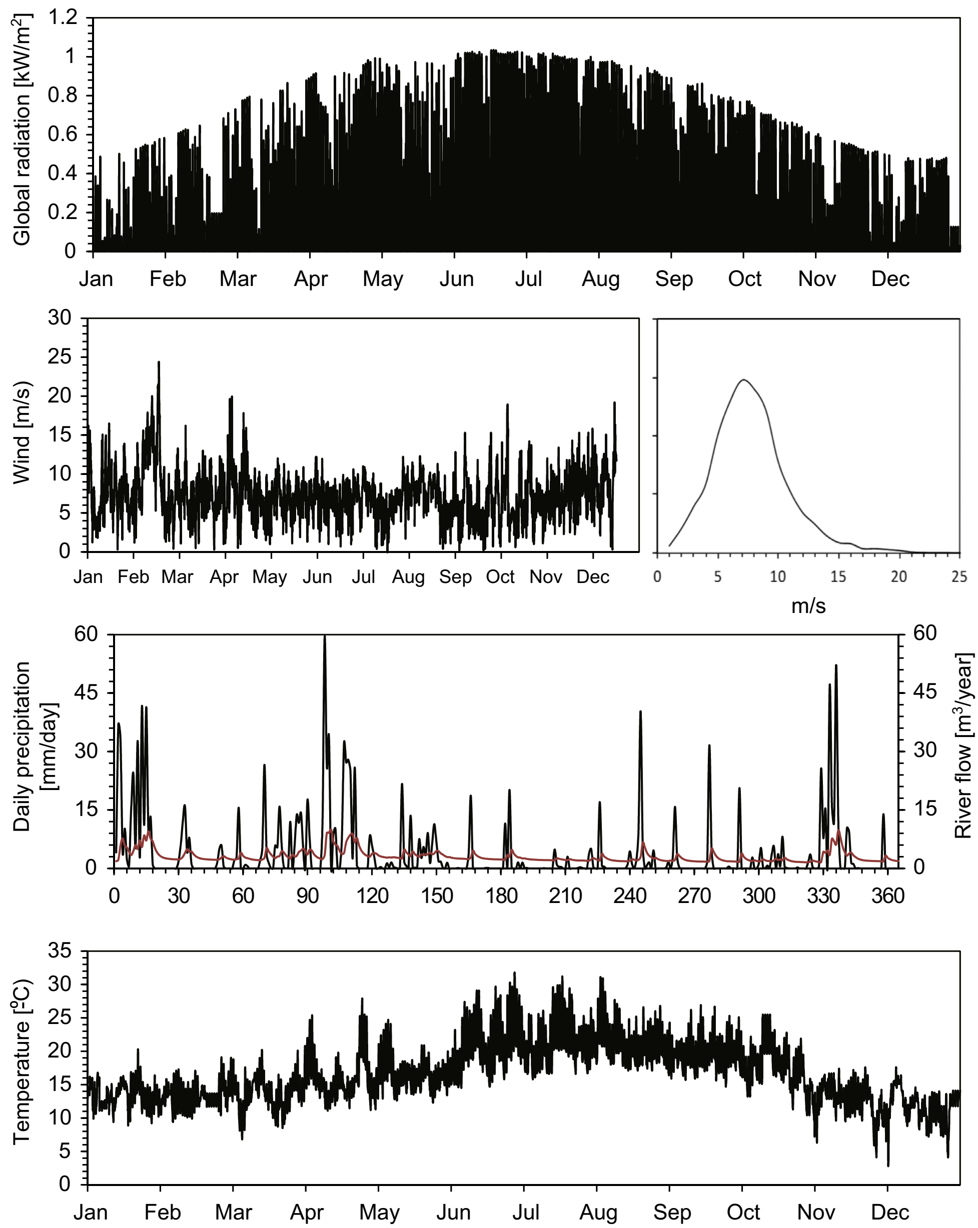

Fig. 1. Input time series: hourly global radiation, wind velocity, precipitation and temperature for a full year. Inset in the wind plot is the wind speed distribution frequency. Red line in precipitation plot shows river flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Parameters characterising the input time series.

	Global radiation	Wind speed	Precipitation	Temperature (°C)
Maximum	1.0 kW/m^2	24.4 m/s	24.3 mm	31.8
Average	0.177 kW/m^2	7.3 m/s	0.17 mm	16.4
Minimum	–	–	–	2.8
Total	1.6 MW h/m^2/year	–	1.47 m	–

technologies that have proven conversion efficiencies and known costs. Interesting technologies which are site-dependent (e.g. geothermal) or still in development (e.g. offshore wind, tidal or wave power) are not considered.

First, the available energy density (kW h/m^2/year), the total resource potential and the cost are estimated for each of the technologies/resources. Then the hourly energy available is determined using the time series described in Section 1.

3.2.1. *Solar power*

Standard commercial photovoltaic (PV) installations have an overall efficiency of about 12% [31] and therefore, given that the total annual radiation is 1.6 MW h/m^2/year (see Table 4), the density of PV electrical energy production is 186 kW h/m^2/year. Assuming a typical installation cost of 3 €/Wp and a lifetime of 25 years [32], the energy cost[1] is 0.08 €/kW h. A more complete approach would be to assess the levelized cost of electricity for a PV system [33,34]. The hourly PV electrical energy is straightforwardly calculated using the solar irradiance time series.

The PV modules may be installed on rooftops. Assuming 20% of the total roof area is used for photovoltaics, and that each family

[1] All the cost estimates in this section assume a unitary capacity factor which means that all the energy produced is fed to the grid and thus costs are determined by dividing the energy produced by the cost of the equipment and its O&M. If, as discussed in detail in Section 4, at certain times some of the energy is not dispatched for whatever reason, the unitary cost of energy will be higher.

(2.5 people) has an average roof area of 70 m^2 then the island may have 28 ha of PV panels, which correspond to an annual production of 52 GW h/year, or 2.9 kW h/person/day. If a larger production of PV is required, one may envisage municipal power plants, such as concentrated photovoltaic (CPV) [35,36] or concentrated solar power (CSP) plants [37,38], which have similar cost and energy potential per unit area.

3.2.2. Wind power

The power density of wind on a plane perpendicular to the airflow is given by

$$P = \frac{1}{2}\rho\, v^3 \tag{2}$$

where ρ is the density of air and v the wind velocity. Applying Eq. (2) to the probability distribution of wind speeds, we have a power density of 458 W/m^2.

Spacing between turbines in wind farms is typically five times the rotor diameter. This spacing is one which minimises the turbulence felt between adjacent turbines. Following [2] and assuming a typical windmill constant efficiency of $\eta = 50\%$, the wind power per unit area of footprint is

$$P = \eta \frac{1}{2}\rho \frac{\pi d^2}{4} v^3 / (5d)^2 = \frac{\pi}{200}\frac{1}{2}\rho\, v^3 \tag{3}$$

where d is the diameter of the windmill. Using the annual probability distribution of wind speeds, by computing the power for each wind speed range and summing all with the respective range frequency, yields an annual production of 64 kW h/m^2/year. More importantly, from Eq. (3) and the wind speed time series, one can calculate the hourly wind power available. Wind energy cost is estimated at 0.05 €/kW h [39,40]. A more detailed evaluation of the wind potential is possible by considering a wind turbine power curve since the wind turbine efficiency η is also dependent on wind speed [41].

3.2.3. Run of the river hydropower

The power one can extract from flow of water through a turbine due to a vertical drop is

$$P = \eta\rho\Phi g h \tag{4}$$

where η is the turbine power conversion efficiency[2] (typically about 80% [42,43]), ρ is the density of water, Φ is the water flow[3], g is the acceleration due to gravity and h is the vertical fall height. Considering the river flow time series calculated in Section 3.1 and assuming $h = 50$ m, we have an average power of 1.1 MW yielding 9.3 GW h/year. The energy density of hydropower in this example is 0.02 kW h/m^2. This value is obtained if we divide the annual energy production by the total area of the island.

Costs of hydropower are always very dependent on location, size and power of turbines, etc. Assuming a typical cost of 2 €/W and a lifetime of 25 years, the energy cost is 0.04 €/kW h [44]. Electricity costs can be higher in places with less favourable characteristics [45].

3.2.4. Biomass

The biomass co-generation power conversion efficiencies considered here are 30% for electricity production and 80% for combined electricity and heat production [42,46]. When the fuels employed are residues from agricultural crops and forestry, where biomass production is 0.5–1.5 t/ha/year and the lower heating value (LHV) is 15 GJ/t, the energy production is 0.0125 kW h/m^2/year. When dedicated energy crops are employed, biomass production increases to about 20 t/ha/year and therefore the resultant values of energy production increase to 0.25 kW h/m^2/year [47,48]. A reasonable estimate for the cost of electricity from biomass is about 0.10 €/kW h [49,50].

3.2.5. Waste

Domestic waste may be incinerated or used to produce biogas which in turn is used to produce electricity in a thermal power plant. According to [2], the production of non-recyclable waste is 1 kg/person/day and has an energy content of about 2.6 kW h/kg. If we assume a power conversion efficiency of 20%, the energy production for the island is 9.5 GW h/year or 0.5 kW h/person/day. The cost is estimated at 0.04 €/kW h [51]. The environmental advantages of waste-to-energy processes must also be highlighted, since CO_2 equivalent emissions are around 3 times lower than those from buried waste on landfills [52,53].

3.3. Heat supply

3.3.1. Heat from solar energy

The yield of hot water using solar thermal systems depends critically on the demand profile, unlike the other technologies discussed above. For simplicity one may assume a constant and relatively low conversion efficiency of 50%, which is a typical value when heat loss and unused solar hot water are taken into account. By taking the solar irradiation time series, as for solar PV, the average production of solar hot water is 2.1 kW h_{th}/m^2/day. This value is very similar to the daily hot water demand per person and thus one could state that 1 m^2/person is sufficient (see Section 4.2). However, because of the mismatch between the summer high insolation and winter high hot water demand, 1 m^2/person would only satisfy hot water needs for about half of the days of the year. If the collectors' area is doubled to 2 m^2/person, the solar fraction[4] is increased from 75% to 90%, resulting in the hot water demand being satisfied in 78% of the days. This increase in panel size will not only result in higher costs but also in almost 60% of the heat being wasted during the summer (Fig. 2). Assuming a lifetime of 20 years and an installation cost of 800€/m^2, the thermal energy production cost is 0.12 €/kW h_{th} for 2 m^2/person and 0.07 €/kW h_{th} for 1 m^2/person.

3.3.2. Heat as a by-product of electric production

A co-generation power plant will produce both electricity and heat. Assuming a heat conversion efficiency of 50%, the production of heat is 0.21 kW h_{th}/m^2/year for agricultural/forestry residues and 4.2 kW h_{th}/m^2/year for energetic crops. The cost for this type of heat generation is difficult establish, since it is a by-product of electricity generation. This will be discussed in further detail in Section 5.3.

3.4. Transport

Vehicle transport must be powered by electricity or biofuels, since the challenge is to develop a fossil fuel free energy system. For assessment of biofuels potential and cost we consider two bioethanol options (sugar beet and wheat) and two biodiesel options (rapeseed and sunflower). The relevant data is summarised in Table 5. The LHV values considered are 21.4 and 38 MJ/l for bioethanol and biodiesel, respectively [54]. One can observe that bioethanol production has a significantly higher yield but at the expense of cost.

[2] This depends on turbine technology and the water flow rate.

[3] One ought to reserve a fraction (e.g. 20%) of the river flow for ecological reasons [80] and therefore one may consider an extra 0.8 × factor in Eq. (4).

[4] Solar fraction is the amount of energy provided by the solar technology divided by the total energy required.

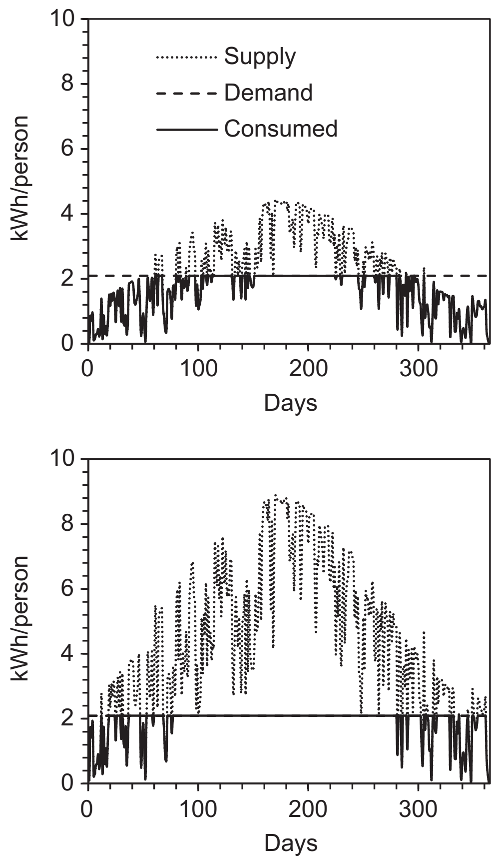

Fig. 2. Solar hot water production, demand and consumption time series for 1 m^2/person (left) and 2 m^2/person (right). Demand is constant at 2.1 kW h/person/day. Production above this value (dotted line) is wasted.

Table 5
Biofuel yield and cost.

	Crop yield		Fuel yield		Cost	
	Crop	t/ha/year	l/ha/year	kW h/m^2/year	€/l	€/kW h
Bioethanol	Sugar beet	66–78	6600–7800	0.111–0.131	0.6	0.10
	Wheat	3.5–9	1225–3150	0.021–0.053		
Biodiesel	Rapeseed	2.8–3.8	1120–1520	0.011–0.014	0.7	0.07
	Sunflower	1.5–3.0	705–1410	0.007–0.013		

3.5. Summary

Table 6 summarises the energy density, total potential and cost for the different renewable energy technologies analysed. Although all energy units are kW h, one should not directly compare electricity with heat or energy from transport. From an educational point of view, the introduction of this table is perhaps an appropriate time for the discussion of the concept of exergy [55,56] [57].

One should highlight that, unlike common perception, solar power actually has the lowest footprint per unit of electricity produced. The island potential for wind power and biomass (and biofuel) does not depend on urban or population characteristics. Their potential depends on the areas assigned to wind parks, forests and agriculture and will be discussed further below.

4. Demand

4.1. Load diagram

The electricity demand is characterized by the load diagram. The simplest approach would be to take a national load diagram and adjusting it according to the population ratio between the island and the country. However, since power demand for a small island may be quite different than that of a larger and much more industrialized region, the island of Faial load diagram is used here. [58] Faial is a small island in the Northern Atlantic with about 15,000 inhabitants, a population density of 87 habitants/km^2 and therefore similar to our imaginary island. The normalization of the load diagram and extrapolation to our imaginary island results in an electricity demand of 8.2 kW h/person/day.

Fig. 3 shows the island average load diagram for three typical days, in different seasons. The overall increase in the power demand for the month of August may be due to an increase in activity and population associated to incoming tourism during summer. The peak observed in the evening in December may be due to increased lighting (as days are shorter) and heating. The data characterising these load diagrams are summarised in Table 7.

There is a repertoire of tools to reduce/shift the load diagram. The most relevant ones are discussed.

4.1.1. Daylight saving

The use of daylight saving strategies (shifting the clock for an hour before the summer/winter) is common in many economies and has other positive impacts beyond the energy discussion

Table 6
Summary of the relevant results for the energy supply.

	Energy density	Total potential		Cost
	kW h /m^2/year	GW h/island/year	kW h/person/day	€/kW h
Solar PV[a]	186	52.2	2.86	0.077
Wind	35.0	–	–	0.023
Hydro	0.02	9.9	0.54	0.009
Biomass	0.26	–	–	0.100
Waste	0.02	9.5	0.52	0.040
Solar hot water[b]	780	32.2	1.8	0.12
Biomass heat	0.42	–	–	n/a
Biofuels	0.01–0.13	–	–	0.07

[a] Considering 20% of the roof area.
[b] Considering 2 m^2/person.

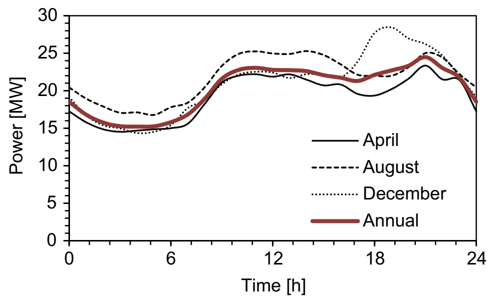

Fig. 3. Load diagrams for three typical days, in three different seasons.

Table 7
Characterization of load diagrams.

		April	August	December	Annual
Energy	GW h/year	167.96	190.85	183.45	177.56
P_{avg}	MW	19.17	21.79	20.94	20.27
P_{min}	MW	14.52	16.78	14.36	15.21
P_{max}	MW	23.35	25.29	28.44	24.48

Table 8
Timetable for differentiated electricity rates.

	Hours
Lower rate	0–8; 22–24
Higher rate	8–22

(e.g. decrease of car accidents in the morning). The impact on energy demand is, however, not as relevant as it is usually presumed [59] and in some situations it may even be counterproductive as a decrease in morning demand may be overcompensated with an increase in the evening demand due to e.g. electricity for cooling. Since there are no cooling needs in our imaginary island, this pernicious effect is not to be expected. Also, since the Faial Island has an ongoing daylight saving scheme, the demand load curve shown in Fig. 3 already takes this measure into account.

4.1.2. Pricing

Price is arguably the most efficient way to condition electricity demand. The increase of the flat rate of the electricity price is known to reduce the demand. However, if the increase is too aggressive it may have a significant negative impact on the local economy [60]. In the scenarios below, an arbitrary increase in flat rate price will be considered to lead to a uniform overall 10% reduction in demand. Realistically, this decrease in demand may be achieved by a careful use of electricity and/or by use of more energy efficient appliances.

Another option is the introduction of pricing according to the time of use [61]. This approach leads to a shift of demand from peak hours (higher rate) to the base load. This will be assumed to result in a 10% shift away from the peak hours, according to the timetable shown in Table 8.

4.1.3. Demand response

In this paper we define demand response as a general term that includes dynamic pricing (electricity rate depends on the instant or near term balance between demand and available supply) and particular customer contracts that reward reducing demand at critical times. For a review of these tools for demand conditioning and its impact see [62]. Here, we assume that the elasticity of demand (the maximum value that a consumer is willing to reduce/increase its demand at a particular time of the day) is 10% of its total demand.

4.2. Heat demand

Heat demand is mainly driven by hot water use and thermal comfort. For the sake of simplicity, we shall ignore other uses of heat, such as those associated to industry. For the estimation of heat demand for hot water we can assume that each person requires 45 l of water at 60 °C per day. Thus the heat required is

$$Q = m\,C_p \Delta T = 2.1\ \text{kW}\ \text{h}_{th}/\text{person}/\text{day} \tag{5}$$

where ΔT is the temperature difference between the inlet (assumed to be equal to the annual atmospheric average temperature) and outlet (60 °C) water temperatures. This accounts to about 38.2 GW h_{th}/year for the whole island.

To determine the heat requirements for space heating, the indoor thermal comfort range is considered to be from 18 °C to 25 °C. For our island, the result is that there is essentially no need for cooling, since temperatures rarely exceed 25 °C (see Fig. 1). However, as almost half of the days in the year have an average temperature below 18 °C, heating will be required[5].

For a rough estimate of the heat requirements for a typical home one may assume the following:

- heat losses by conduction with an average U value of 2 W/m^2 K for a $10 \times 10 \times 2$ m^3 home;
- heat losses due to air replacement (ventilation) of 1 ach;
- solar gains of 2.33 kW h/m^2/day and 0.83 kW h/m^2/day for south facing and east/west facing walls, respectively;
- internal gains of 100 W/person considering 2.5 people/home for 12 h/day plus 2 W/m^2 from appliances;

We can thus determine the daily net heat required to keep homes within the comfort temperature range. The annual net heat required is almost 2 MW h_{th}/year per home, which leads to 38.5 GW h_{th}/year for the whole island, quite similar to the heat demand for the hot water. This heat demand is obviously concentrated in the cold season.

4.3. Transport scenarios

The imaginary island is designed to be fossil fuel free and therefore the transport needs will be addressed by electric vehicles (EV) and/or biofuels. Electric vehicles will obviously add demand to the load diagram discussed in Section 4.1 while biofuels will compete with biomass and food, etc., for available land.

The first step for the analysis of the energy required for the transport sector is the assessment of the energy demand per km-person for the different transport options[6] (cf. Table 9).

As expected, public transport has lower energy consumption due to the number of people on board. It should be noted however that the difference between individual cars and buses running on biofuel (almost a factor of 4 ×) is much higher that the equivalent difference for electric vehicles (only a factor of 2 ×), thus showing

[5] One may argue that by considering average day temperature instead of hourly temperature we are taking into consideration the building thermal inertia.

[6] It is also interesting to compare the amount of energy used by a car throughout its lifetime and its embodied energy. The latter may be estimated by assuming that the cost of the car is only due to its embodied energy: assuming a low cost of electricity at the manufacturing site of, say, 0.05 €/kW h, and a total cost of 15 k€ we get 300 MW h/car. Assuming that a car uses 1 kW h/km and drives about 10,000 km/year, it would take 30 years for the car to spend on fuel as much energy as it was required to make it in the first place.

Table 9
Energy needs for transportation.

Type	Fuel	Vehicle	l/100 km	kW h_e/km	No. passengers	kW h/km-person	Refs.
Passengers	Biofuel	Car	10		1.5	0.667	[81]
		Bus	52		30	0.173	[82]
	Electric	Car		0.20	1.5	0.140	[83]
		Bus/trolley		2.83	30	0.094	[84]
		Subway		2.39	80	0.030	[84]
Goods	Biofuel	Truck	32		n/a	n/a	[85]

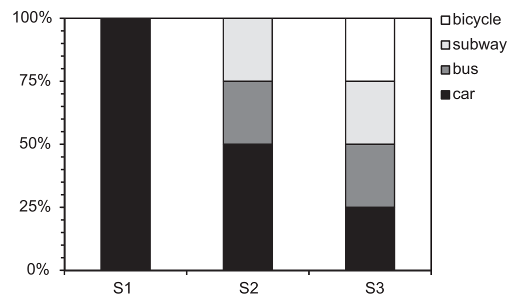

Fig. 4. The different mobility scenarios.

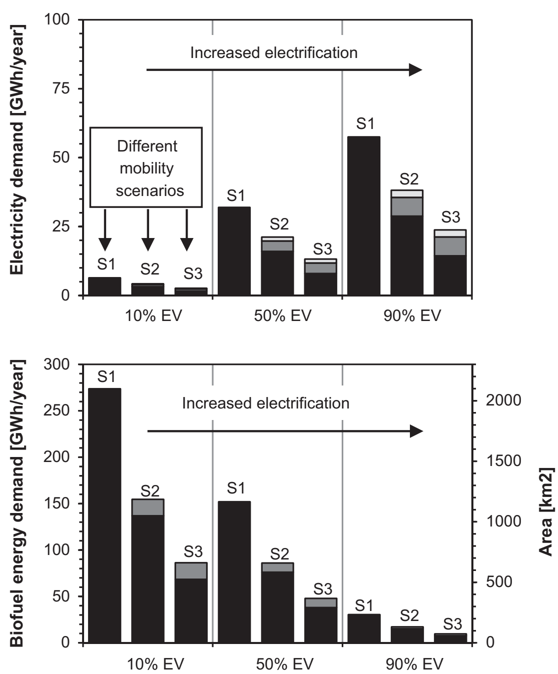

Fig. 5. Energy demand for the transport sector: electricity (top) and biofuel energy (bottom) demand for different mobility scenarios (S1–S3) and increased levels if electrification.

that new electric cars have indeed an overall very good energy efficiency. For simplicity, the transport of goods within the island is not considered.

The purpose of this section is to determine the energy demand for the transport sector. We shall define 3 possible mobility scenarios (S1, S2, S3) for different use of individual car, public transport (bus or subway) and walking/biking (cf. Fig. 4). It is also assumed that local habitants travel on average 25 km/day.

Using the data from Table 9, and assuming 3 levels of penetration of electric vehicles (replacing both individual cars as well as buses running on biofuels) we can calculate the energy demand for the transport sector, as shown in Fig. 5.

The results confirm that the use of public transport leads to lower energy demand. Also obvious, the higher the level of electrification of the fleet, the higher will be the electricity demand and the lower will be the demand for biofuels.

The left vertical axis on both plots of Fig. 5 refers to final and not primary energy and therefore may not be directly compared. However, it is interesting to note that the maximum energy demand for biofuels (everyone driving individual cars running on biofuel) is significantly higher than the maximum electricity demand (everyone driving individual electric cars). This statement holds even if all electricity were to be produced from biomass (cf. Section 3.2) thus asserting the relative high efficiency of electric cars.

Also, the right vertical axis of the biofuel plot shows the land demand for the growth of energy crops for transportation (assuming the production of bioethanol with the highest yield, cf. Table 5 in Section 3.4; for biodiesel the required area would be 10 × larger). Remembering that the island total area was set to be 500 km^2, it is evident that a significant level of electrification of the transport sector is required, together with efficient mobility scenarios.

Finally, it is also interesting to note that even for the most favourable mobility scenario (when half of the population uses public transportation and 25% only use energy from metabolism to move around) with 90% of electrification, leads to demand of electricity of the order of 1.3 kW h /person/day, adding about 1/6 to the average daily electricity demand in the island.

It is thus essential to review some of the management tools to promote a more favourable mobility scenario, which leads to lower energy demand (regardless of the ‘fuel’). The most common solutions available to decision makers are based on penalizing the individual transport by taxation or expensive parking rates, implementing bus lanes [63] or park & ride solutions [64,65]. These may have a significant impact on the shift of usage from private to public transport. Nevertheless, as one considers the energy intensity for transport in Table 9, and in particular for EVs, it is very clear that a small increase in the occupancy rate of individual cars has a huge impact on the energy demand. Thus, car pooling solutions [66] ought to be implemented in the imaginary island to achieve scenario S3.

The energy demand for these mobility scenarios could be further reduced if the averaged travel distance was to be reduced, which could be achieved by concentrating the population in the urban area. This fact serves as a good opportunity to highlight and discus with the students the energy sustainability of urban vs rural populations [67].

5. Storage and transmission

5.1. Electricity storage

There are different technological approaches for electricity storage. For a review see [68]. Here, for simplicity, only the following are considered: large scale storage dam with pumping storage and decentralized small scale using electrochemical batteries in homes and/or in cars.

Table 10
Main characteristics of electrochemical batteries.

		Lead	Li-ion
Specific power	W/kg	130	300
Specific energy	W h/kg	33	140
Efficiency		80%	90%
Cost	€/W h	0.09	0.13
Lifetime	cycles	1500	3000

5.1.1. Hydroelectric storage

Pumping water up a dam at low demand hours is a well established procedure for electricity storage [69]. Assuming a $2 \times 2\ km^2$ reservoir area with an average depth of 20 m and a conversion efficiency (for the generation of hydroelectricity) of 90%, one can hold the equivalent to about 0.7 GW h of electricity in the reservoir (for a pumping efficiency of 80% this would correspond to almost 0.9 GW h of electricity required to fill the reservoir).

When the pumping station is introduced, one may increase the installed power (in Section 3.2 the installed power was limited by the available water flow). The sizing of the new turbines will therefore have to take into account the needs for energy storage of the island. Assuming a ten-fold increase of the installed power (21 MW), using Eq. (4) we get a water flow of $121\ m^3/s$ and therefore a discharge time[7] of about 184 h.

Regarding costs, the added cost for a pumping loop to a dam during construction is around 30% of the total investment cost on the hydroelectric plant, which leads to a storage cost of 0.47 c€/kW h.

5.1.2. Batteries

Small scale decentralized electrochemical batteries will be available in electric cars (Li-ion) and perhaps in the homes (lead acid) coupled to solar home photovoltaic systems. Table 10 summarizes their most relevant characteristics.

Lithium-ion batteries are more expensive, but they have higher energy density, higher efficiency and last longer. Either way, costs are orders of magnitude higher than the pumping storage and thus the use of batteries cannot be economically viable if its primary use is as energy storage for the grid; hence the use of these coupled to PV systems does not hold economically.

For electric vehicles, the battery technology of choice is lithium-ion due to the advantages mentioned above. We assumed for each car a total battery capacity of 24 kW h, from which 70% is effectively used (to consider for deep discharge prevention and capacity losses that happen over time) and that, on average, 90% of the fleet is parked [70] and connected to the grid. Thus, for a 100% EV fleet (25,000 cars, scenario S1) one has 0.28 GW h available for vehicle-to-grid (V2G), which corresponds to a buffer of about 15 h, considering the average load on the island of 19 MW. The maximum storage capacity in the batteries is thus about 6% of the pumping storage capacity. As far as costs are concerned, one may assume that the use of the EV batteries for grid back up will lead to an accelerated aging of the battery and therefore its precocious replacement. In the model we considered that the lifespan of the battery is reduced by 3 years (7 years instead of the normal 10 years) [71]. If the cost of the battery is €20,000 [72], this leads to a V2G cost of 0.19 €/kW h.

5.2. Electricity transport

The construction and maintenance of the electric grid on the island will lead to energy losses and added costs. These are difficult to estimate, in particular for a small island, since they depend on the distribution of the population on the island, the number of substations, the percentage of underground lines, the voltage use, etc. For our imaginary island one will assume average energy losses of 8% [73,74] and an added cost of 0.01 €/kW h.

5.3. Heat transport

The co-generation biomass plant will produce excess heat that could be used for water or space heating and therefore it is interesting to analyse the costs and energy losses associated to district heating. The distribution of heat may be achieved by water vapour or hot water. This second option, suitable for lower temperature uses, leads to lower costs (0.01 €/kW h for a 10 km line) [75] and lower losses (about 15%) [76]. However, for the mild climate of the island the district heating option cannot be economically competitive and has been discarded. Thus, the solution for the heat supply and demand is based on $1\ m^2$/person solar thermal panel complemented by electricity heating. For hot water one can assume a coefficient of performance (COP) equal to 1, which is basically Joule heating, whilst for spacing heating one can assume heat pumps with typical COP values of the order of 3. This electricity demand for heating has been factored in for the electricity demand time series discussed below.

6. Results

Considering the data described in the previous sections, one can now build an energy system model for the imaginary island. All calculations below were performed on a spread sheet using the built-in optimization engine. For all optimizations, the free variables are the area available for biomass and photovoltaics, the number of wind turbines and the dam installed power.

The first approach, named Model 1, focuses on the annual net electricity production, i.e. how much electricity one would have to produce annually in order to cope with the annual demand? The main characteristics of this model are:

- The selection criterion for the supply portfolio is cost and therefore the implementation area for the different electricity supply technologies can be such that they are set to their maximum local potential according to Table 6 above.
- Transports are assumed to be driven by biofuels and thus do not add electricity demand.
- As discussed in Section 5.3, heat demand is satisfied by solar hot water complemented by electrical appliances.
- In order to avoid situations where demand surpasses local supply, one may assume for this first model that the island is connected to a wider electricity system, e.g. the continental grid, via an underwater cable with an electricity cost of 0.15 €/kW h.

The results are summarised in Table 11. The cost criterion leads to the focus on the least expensive technologies and therefore the optimized energy mix does not include solar or biomass.

In Model 1 the annual energy imported/exported reaches 74.5 GW h/year with a maximum power of 22.5 MW. Assuming no energy storage, if there was no connection to the continental grid then the local electricity supply would have to satisfy all the electricity demand at all times during the year, and the installed power would be severely oversized. In fact, there are some windless hours when the sum of all other electricity sources is unable to fulfil the demand unless almost 15% of the island was used for the growth of biomass. This *brute-force* approach would of course be clearly unrealistic.

[7] This is equal to total volume divided by maximum flow.

Table 11
Model results: energy portfolio, power and costs.

	Model 1 Annual net Import/export	Model 2a Hydro storage no import/export	Model 2b EV storage no import/export
Solar	–	–	52.1 GW h
Wind	130.1 GW h	190.9 GW h	1136 GW h
Hydro	9.3 GW h	9.3 + 40.7 GW h	9.3 GW h
Biomass	–	–	49.9 GW h
Waste	9.5 GW h	9.5 GW h	9.5 GW h
Total power installed	46.8 MW	86.5 MW	400 MW
Annual electricity demand	150 GW h	159 GW h	218 GW h
Annual electricity supply	207 GW h	250 GW h	1256 GW h
Capacity factor	41%	33%	5%
Cost	10.5 c€/kW h	4.7 c€/kW h	25.0 c€/kW h

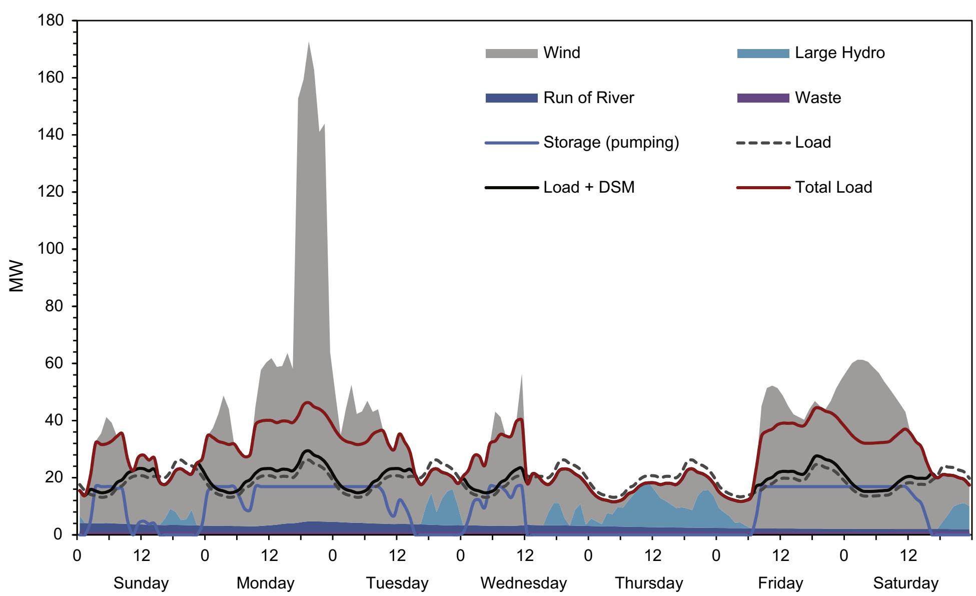

Fig. 6. Load diagram for a week in January for the island energy system with hydro storage (Model 2a).

From these results it is clear that some sort of energy storage is required. Models 2a and 2b describe two extreme scenarios for energy storage:

- Model 2a considers storage in a reversible dam, while transport is still mostly guaranteed by biofuels (scenario S3 with 10% electric vehicles that add to the electricity demand but are not used as backup for the grid);
- Model 2b considers a 100% fleet of electric vehicles (also in scenario S3) whose batteries are used as back-up for the grid.

Furthermore, both models consider the implementation of demand response mechanisms in order to reduce demand at peak times. As above, the optimizing criterion was final cost of electricity.

Fig. 6 illustrates the renewable energy mix calculated for a typical week in January using Model 2a. One can note the over-supply of wind power in about half of the time. The effect of the demand side management (solid black line, compare with dotted black line) is insufficient to overcome the wind power variability and therefore the energy stored in the dam becomes critical for the management of the energy system. The massive wind power oversupply on the second day is followed by two windless days that require power from the dam.

Since it does not require the import of expensive electricity from abroad, Model 2a is able to halve the final cost of electricity. Comparing with Model 1, the installed capacity is increased (to pump water to the reservoir when excess energy is available) and therefore the capacity factor is slightly reduced.

On the other hand, Model 2b uses the EV batteries for back up of the grid. Of course, this option leads to an increased electricity demand. A simple algorithm for energy management of the EV batteries was developed, taking into account the electricity supply/demand balance of the following 24 h: EV batteries are charged at the most favourable times of the day. This method assumes that the energy levels of the EV batteries are controlled by the grid but guaranties an autonomy of 25 km/day for all cars. Notice that, with this simple model, EV charging patterns are not optimized according to their driving needs (e.g. morning drivers may be upset if the most favourable charging time is noon). Furthermore, it assumes that wind and solar power variability are predictable 24 h ahead and other simplifications that are not necessarily realistic. For a detailed discussion of energy management of EV batteries see [77].

Fig. 7 shows the load diagram of a week in July for Model 2b. Since the capacity of the V2G buffer is much lower than the dam reservoir, the energy system requires larger installed capacities (in particular wind power) leading to a much lower capacity factor (cf. Table 11). The added cost allows for the introduction of biomass and solar PV, which now become cost competitive with storage.

In order to increase the storage capacity one can increase the number of EVs. On the other hand, increasing the number of vehicles will lead to increased electricity demand. Thus, there must

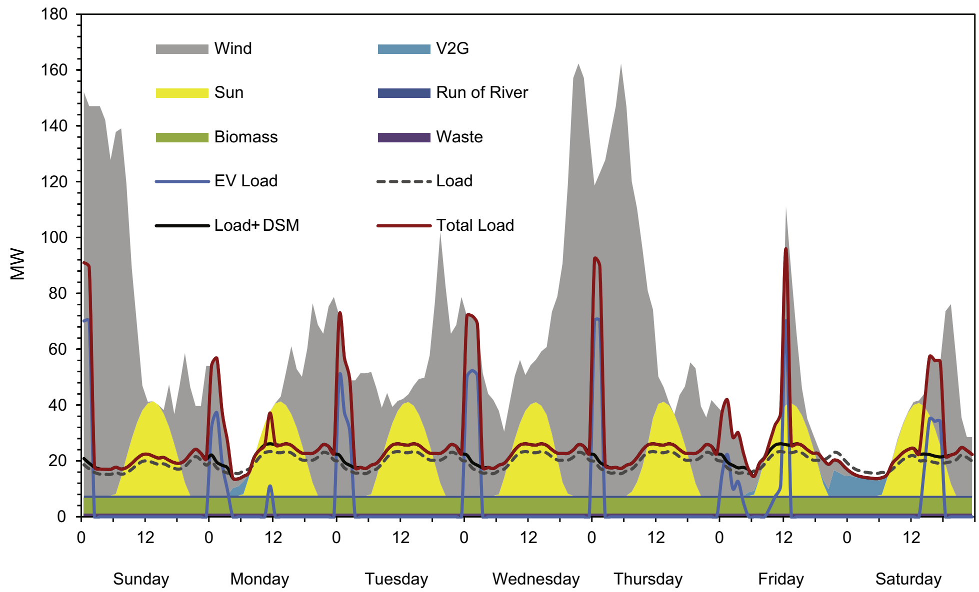

Fig. 7. Load diagram for a week in July for the island energy system with EV storage (Model 2b).

be an optimum of EVs which will minimize electricity cost whilst maximizing the capacity factor. This optimum is shown in Fig. 8.

It is interesting to notice that if we take the values shown in Table 9, where the energy consumption for EVs and biofueled vehicles is 0.14 kW h/(km person) and 0.667 kW h/(km person) respectively, and then using the respective energy cost of electricity of at most 0.30 €/kW h (as shown in Table 11) and biofuels of 0.667 €/kW h (see Table 6), the transport cost is 0.042 €/(km person) and 0.047 €/(km person). This suggests that that transportation in EV can always be economically viable for the user.[8]

Finally, it is important to mention that a complete discussion of sustainable energy systems for a remote island ought to consider some other discussion topics such as:

- Need for redundancy in an isolated energy system in order to increase the robustness of the energy system for unfavorable weather conditions (such as long cold spells, unusual windless or sunless weeks) or interruptions for maintenance;
- Any discussion of biofuels for mobility ought to analyse their impact on the food crisis and in developing countries [78,79];
- Costs of de-fossilizing the energy system;
- Climate change impact on renewable energy resources.

7. Conclusions

We have developed a model for the energy system for an imaginary island, including electricity, heat and transport. The system ab initio required to be fossil-free and sustainable and it is thus based on renewable energies and local resources only. Different mobility scenarios, energy storage alternatives and demand management instruments are discussed in detail.

The most relevant results are:

- Due to the relative mild winters, district heating is not cost competitive and therefore the heat demand is satisfied via solar hot water complemented by electricity for both hot water and thermal comfort.
- Mobility scenarios based on individual transportation are very energy intensive and therefore it is essential that city planning and energy policies focus on the development of public transportation, car pooling schemes, etc.
- Electricity storage is of paramount importance for an energy system based on renewable, and therefore varying resources. The energy storage may be achieved by either pumping storage or large scale deployment of electric vehicles acting as a back-up to the grid.
- Using present day costs for the technology, the cost of electricity was estimated to be below 0.05 €/kW h, or 150 €/person/year, which is more expensive than today's typical electricity bill but still should be manageable without too many economic and/or social consequences. Learning curves for the different technologies considered show that these costs will surely decrease in the near and medium term, making renewable energy systems even more cost competitive.

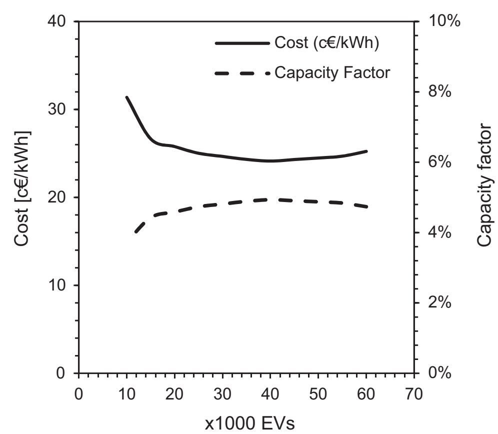

Fig. 8. Electricity costs and overall capacity factor as function of the number of EV.

However, more important than these particular results discussed above, which of course depends on the different assumptions described above, this paper proposes a methodology for the analysis of energy systems that can be used in class in order to

[8] A typical diesel powered vehicle consumes 5l/(100 km). If we assume a cost of 1.5 €/l, then the transport cost of the vehicle associated to fuel consumption is 0.075 €/km. If the vehicles transports on average 1.5 people, the cost is then 0.05 €/(km person). However, diesel is a heavily taxed commodity with the actual cost being far less.

present the most relevant issues regarding energy systems, energy management and renewable energies.

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